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GAINING CONFIDENCE IN MODELS OF EXPERIEMENTS IN EXISTING BUILDINGS

Dr. Jon Hand[1], Dr. JaeMin Kim[1], and Kyunghun Woo[2]
[1]ESRU University of Strathclyde, Glasgow Scotland, G1 1XJ
[2]Green Technology Research Institute, Samsung Construction, Seoul South Korea
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ABSTRACT

A recent project between the University of Strathclyde in Glasgow and Samsung Construction in Seoul highlighted a number of issues related to the creation of models targeted at matching observations and predictions via short term experiments within existing high performance buildings. High performance buildings often include complex sections which are difficult to represent with whole-building models. This paper will report on the influence of the level of model geometric and constructional detail on medium term performances and fit to short term experimental data.

Methodologies for the design of ad-hoc experiments and models is needed for buildings with extreme details. The authors discuss user directed explorations of performance data during calibration phases as well as methods which increase confidence in models.

INTRODUCTION

Buildings which are designed for extreme reductions in energy demands, for example those built according to PassivHaus guidelines or which are intended to exhibit cutting-edge green technologies, pose a number of challenges for whole-building simulation:

* complex building sections where thermal bridges and multi-dimensional conduction is a noticeable fraction of the overall heat transfer

* a mix of thin and thick facade elements resutling in considerable differences between the inner form of the building and the exposed facade

* air-tight construction is essential and faults in implementation can lead to uncertainty in performance

* the spacial and temporal distribution of solar gains and casual gains is of critical importance

* a mix of design ideas assumed to work together but are difficult to evaluate in combination

In non-conventional buildings the above challenges lead to questions about confidence in whole-building simulation tools as well as the skills of practitioners in devising appropriate models and assessments. There is patchy guidance on the design of virtual representations of non-conventional buildings (Hand 2008 and 2010). Of the few user manuals that discuss related topics, only a fraction of the model design issues which arose in this project were covered (Hand 2010).

Currently, assessments used by groups such as the PassivHaus Institute rely on spreadsheet implementations of CEN standards (PHPP users manual) which are geared to annual and monthly reporting of energy use and (with many caviats) summer overheating risk. Although there is evidence of a good fit to observations (Schnieders 2006), designers who have interests in how the buildings perform in detail must look to other tools.

The fit between actual building performance and predictions has been a long-running issue in the simulation community. The Center for Integrated Facility Engineering at Stanford University has addressed a number of issues related to assumptions and approximations that plague both the measurement and simulation fields (Maile 2010a 2010b). Formal validation projects undertaken with well matched test cell buildings and virtual models are beyond the scope of many design teams. Extreme detailing and thermal bridges are missing from validation projects such as BESTEST (Judkoff 1995). This paper explores confidence building actions which could be applied by design teams who wish to explore extreme designs on a limited budget.
For this paper a recent joint project Samsung Construction Institute of Green Technology focused on issues of simulation confidence is described. Confidence issues related to uncertainties in input data (climate, constructions, occupancy patterns etc.). The project included tasks for the direct comparison of observations in a high performance building with the multi-domain simulation tool ESP-r (ESRU 2011). Many of the issues discussed are applicable to other whole-building simulation suites.

The building selected for testing was Samsung's Green Tomorrow (GT) building in Suwon, South Korea. It shares many design goals and details with standards such as PasivHaus. It was the first LEED Platinum rated building in South Korea. Figures 1, 2, 3 and 4 are indicative of the complexity of its form and composition.

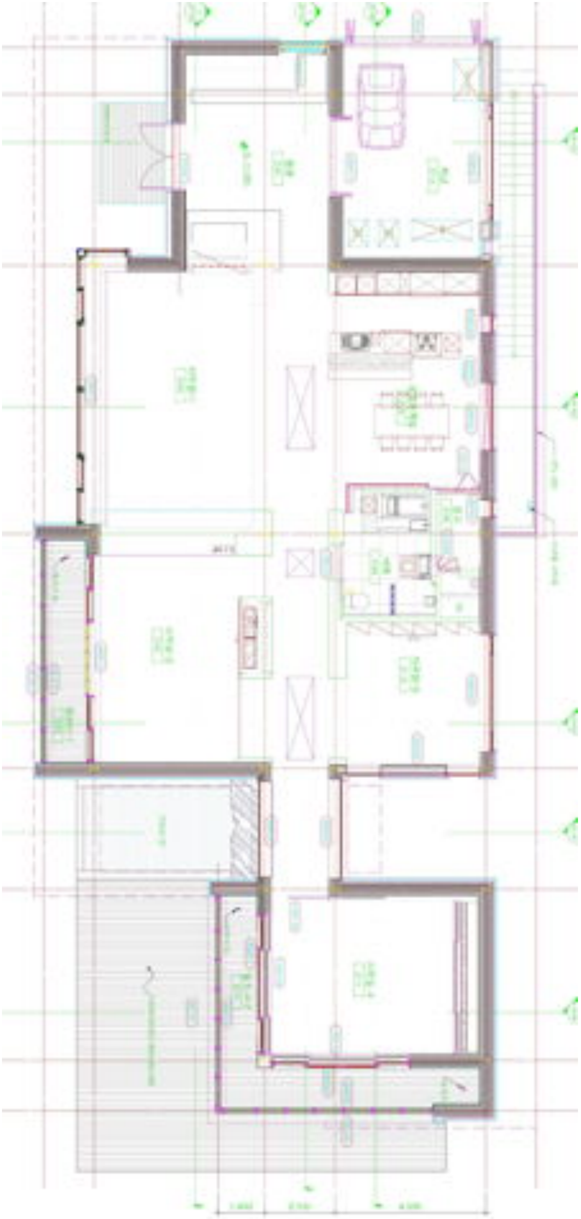

Figure 1 Plan of building (South on left)

Figure 2 Green Tomorrow view from South East

Figure 3 Section with thick and thin façade elements

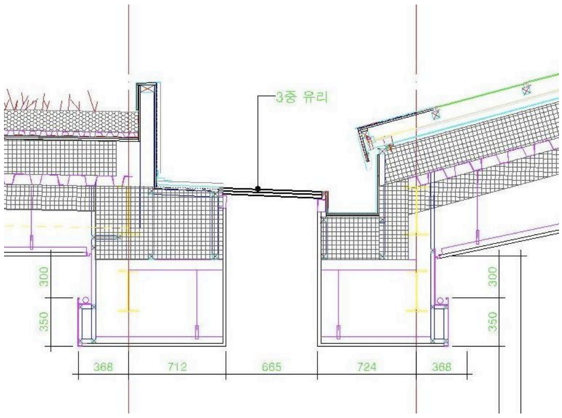

Figure 4 Detailed section at roof over Kitchen

The mix of thick and thin facade elements challenges many of the default assumptions 1D heat transfer and zone enclosures of whole-building simulation. The inner and outer form of the building are substantially different. There are ceiling voids as well as light shafts and service voids and each facade has multiple construction types. The reveals of some windows have a greater surface area than the glass. In some rooms the inside surface area greatly exceeds the outside area. In others, such as the Korea room at the east end of the building, the ceiling area is much smaller than the exposed roof and related facade.

Green Tomorrow also included a version of the traditional Korean floor heating Ondol driven by a ground source heat pump. Ondol are, by definition, slow responding systems which alter the radiant environment in residences to counteract heat losses in low performance building facades. Its use in this high performance building presents both real and virtual control issues. Explicit representations of Ondol are difficult for some simulation tools so one of the goals of this project was to see how well simulation tracks observations.

One room of GT was a traditional space bounded by a paper screen, sliding high performance doors and an outer buffer space with a folding door façade (see bottom of Figure 1). Many of the characteristics of GT were found in this room and it could be isolated during experiments if required.

VIRTUAL AND PHYSICAL EXPERIMENTS

In order to scale up from this demonstration building Samsung wanted to better understand its performance and to determine if in-house skills could support future projects. Since the building was actively used the scope for on-site investigations was constrained. Although additional data gathering devices could be brought to the site it would not be possible to embed sensors or to disturb the fabric of the building.

The goal of the experiments was to identify the fit between real and virtual observations for specific performance topics as well as looking at the impact of model resolution on determination of the overall thermal characteristics of the building.

Testing on site before the experiments included a blower door test, a smoke test and IR survey to identify leakage characteristics and façade fault locations. Such tests provide leakage characteristics at the whole building. As mentioned in Walker (1988) there is uncertainty in the distribution of leakage to individual facade elements. The smoke test identified faults but not the magnitude of the individual leakage paths as required for a dynamic flow analysis. Prior to the blower door tests a number of portable temperature and humidity sensors were distributed around the building (see Figure 5).

Figure 5 Typical portable measurement points

The marginal cost of additional observations can be surprisingly small. For example, at the conclusion of the blower test a one hour forced purge of the building was undertaken (the delta T approached 40C) and the rate of air and temperature depression was noted from the portable loggers along with their recovery over the next two hours. This yielded vital clues about the building which were incorporated into the virtual models.

Response characteristics to step changes are a classic test of simulation tools (and of buildings). The author observed the conclusion of a 10 day heat-off response test on an Austrian PassivHaus where an overall drop of 5 degrees from an initial 21C starting temperature was recorded with an average outside temperature over the 10 day period of -10C (Rothele 2010).

Thus, the first *deceptively simple* experiment for Green Tomorrow was to look at air and surface temperature patterns in the Korea room, alcove and buffer space if heating was stopped for 24 hours and then restarted during extreme winter conditions. Informal observations of the response in other parts of the building were also carried out. To isolate solar effects, the experiment began late at might and then after ~eight hours solar radiation impacts on air and surface temperatures would be more clearly delineated

The virtual requires an accurate solution of heat storage in the mass of the building as well as each heat loss path during the off state. The ability to characteristic the response of the Ondol during cool down and startup phases was also essential. Given that infiltration and conduction were constrained by design the authors were particularly interested to find out which loss dominated at each phase of the experiment and whether stratification was observed.

The large openings between rooms in Green Tomorrow suggested that disturbances in air temperatures would impact adjacent spaces (much as they do in open plan commercial buildings). This was clearly the case for the entrance door and the adjacent living room when the door was opened and when occupants entered the buffer spaces in Green Tomorrow. Buffer spaces are ubiquitous in Korea as are sliding doors. In Korea one must also consider the interactions between disturbances in air temperature with the slow responding Ondol.

The temporal measurement of mass flow within rooms typically involves multiple tracer gas measurements and thus specialist equipment and extended setup times (Niachou 2007). Many design teams would find direct flow measurement is beyond the scope of their projects. However, air movement impacts surface and air temperatures which are much easier to measure. This suggests an alternative approach of using temperatures at different locations over time as a proxy for air movement measurements. The predicted surface and air temperatures could then be compared with observed surface and air temperatures.

ESP-r includes a mas flow solution tightly linked to the zone solver. A good test of simulation would be to see numerical methods could track an experiment that involved a step change in air movement and interactions with the Ondol.

The *deceptively simple* second 'slider' experiment involved opening the paper screen and sliding door between the Korean room and the buffer space for four hours and to observe the evolving state of the room and the subsequent recovery. Agai, the experiment begins in the evening with conditions tracked for the preceding 12 hours.

The involveds rapid changes in the driving forces for air movement, convective regimes and radiant exchanges as the Ondol attempts to correct for the fall in temperature and later as the door closes and the Ondol eventually switches off. Fully transient responses are required and almost all aspects of the simulation tool would be exercised. If simulation matches temperature measurements then the rate of air flow is also likely to track the actual (but unmeasured) flow.

MODEL RESOLUTION ISSUES

The design of models involves a series of decisions regarding the zoning and composition of models needed to support specific assessment issues. An overly simplistic model may not be able to represent the underlying characteristics of the building or deliver the specific types of information needed to judge performance. Where the model is intended to reflect short term observations additional care is needed to ensure the essential characteristics of the building are captured.

To reduce uncertainty, virtual measurement points should match actual sensor locations as much as possible. This requires careful consideration of the context of each sensor and adjustment in the design of the model zoning, polygon positioning and constructional composition. For example, a sensor embedded in a wall that has a 3 degree temperature variation across its surface (perhaps because of sun patches) may not be well represented by a model with a single surface representing the wall. An IR survey might reveal thermal bridges near a sensor location which should be reflected in the composition at that point.

The east portion of Green Tomorrow selected for the two experiments includes the traditional Korean room, an adjacent alcove (separated by a paper screen) on the north, spaces between the room and the buffer space formed by a paper screen on the south and east sides of the room as well as the buffer space itself and the ceiling void. We might represent these air spaces, each of which might have a unique temperature, separately (the most explicit option). We could ignore some of them (such as the gap between the paper screen and sliding door) or combine them (Korea room and alcove).

The open door experiment involved 1500 time steps (minutes) of data. The driving forces are transient and tightly linked to evolving boundary conditions (room surfaces and the Ondol heating system). For this project a decision was made to approach the assessments via simultaneous building and mass flow network solution running at the same timestep as the data collection. ESP-r includes a bi-directional air flow component for doors which is based on the assumption of equal height spaces on each side of the door. However, if zones are sliced horizontally the air flow across the doors need to use a pair of common orifice flow components.

One would expect a strong floor - ceiling heat transfer path due to the radiant portion of the Ondol heat delivery. One might also expect some stratification during the warm-up phase. Sub-zoning of rooms to support higher resolution requires the introduction of separating surfaces which may not greatly constrain the movement of air and short wave radiation but does impact long-wave radiant exchanges between the separate zone slices. One cannot have high radiant exchange resolution and air temperature resolution at the same time.

MEASUREMENT REGIME

To support these two experiments air temperatures at 15 points and 10 surface temperatures were tracked at one minute intervals from 12 hours before each experiment to 12 hours after each experiment. One of the columns of thermocouple sensors is shown in Figure 6. At the floor, ceiling, frames and glazing thermocouples were fixed to the surfaces and radiantly shielded. Portable temperature and RH sensors placed in boundary locations. This project was attempting to use data gathering kit which could be brought to site in a couple of duffle bags rather than the scale of whole building sensor arrays employed in the Stanford research projects.

Software was created to take in pairs of data from measurements and from the simulation tool and undertake a statistical analysis. The fit between the two is expressed as a standard correlation coefficient (Scheaffer and McClave, 1982).

Figure 5 Column of air sensors

Thiel's U inequality coefficient (Williamson, 1994) which provides a measure of how well a time series of simulated values compares to a corresponding time series of observed values. A U closer to zero indicates a better fit. The matching rate is calculated from (1- U) x 100 %.

User pattern matching skills were augmented by checks on matching rate and CC for various points. For example, Figure 7 shows the best match between measured and simulated temperature profiles on the surface of the ceiling with a matching rate 99.2% and CC of 0.98.

There are limitations in improving matching rate despite the calibration process. As can be seen in Figure 8, the matching rate is 96.3 and the CC is 0.86 because the initial floor temperatures differ. The Ondol heating turn-on and turn off has a long cycle. In simulation the heat pulse happens just before the slider experiment started but was ~1.5 hours before in the experiment. The response while the slider is open and after it closes is much closer. This is likely to be a general problem with matching measurements in a slow response experiment.

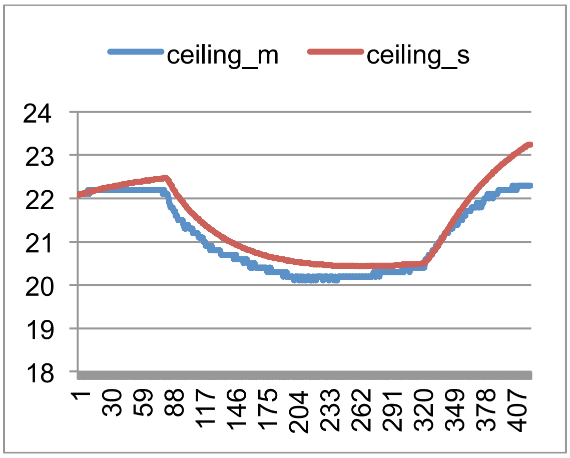

Figure 7: temperature profiles of measured (ceiling_m) and simulated (ceiling_s) surface.

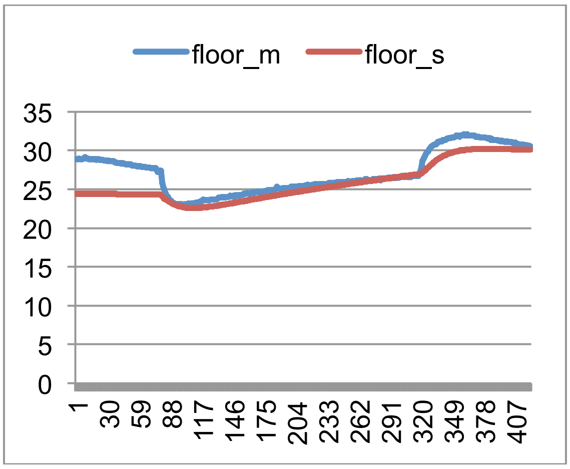

Figure 8: temperature profiles of measured (floor_m) and simulated (floor_s) on the surface of floor.

MODEL VARIANTS

One goals was to check variations in short and long term performance predictions which might result from different sub-zoning strategies. To clarify such choices the following model variants were created:

Low resolution base case (LOWBC) - the alcove and sliding doors voids were included in the Korean room and the inner and outer façade geometries were simplified (but surface areas were preserved). The Ondol was explicit as was the ceiling void and a flow network was used to represent air movement. A heat transfer coefficient regime for floor heating was used.

Low resolution without explicit roof (XRF) - as LOWBC but with the ceiling void represented as an air gap in the ceiling construction.

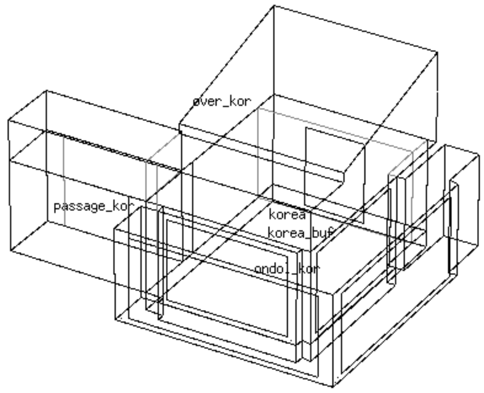

Figure 9: model for LOWBC

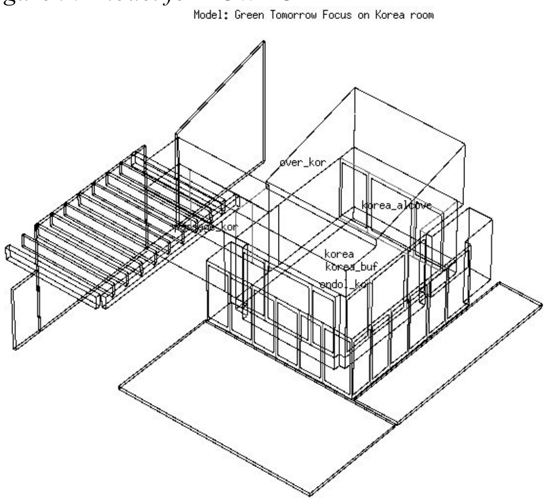

Figure 10: model for MIDBC

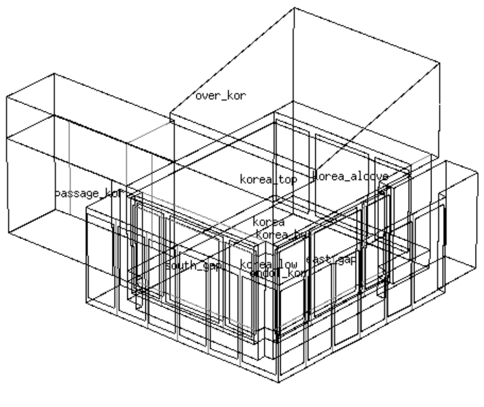

Figure 11: model for HION

Low resolution without explicit Ondol (XOND) - as LOWBC but heating was represented as a sensible convective source (the mass of the Ondol was preserved).

Low resolution with scheduled infiltration (XMF) - as LOWBC but with infiltration defined as a schedule.

Medium resolution base case (MIDBC) - with glazing and frame geometry represented and the alcove as a separate zone.

Medium resolution with addition leakage paths in air flow network (MID2XF) - as MIDBC but with double the length of cracks in the facade.

High resolution geometry (HION) - Korean room as low middle high slices, gap between paper screen and sliding door included and external slats on buffer room explicitly represented.

MODEL CALIBRATION

The authors wished to avoid brute-force parametric excursions or trial and error approaches that did not involve a clear methodology. The measurements and the data store generated by the assessments provide a wealth of information for staff who already have good pattern matching skills and an understanding of the underlying physics as well as providing an excellent platform form which to develop these skills. The user directed calibration based on an evolving understanding of what was actually happening during the experiment and matching this with the virtual measurements points (see Figure 12) and derived data in the simulation environment is discussed next.

An initial set of model changes related to gaps in the documentation about the experiments - it was not clear whether the lights and/or the Ondol were on during the open door experiment. Model variants were made and the statistical fit and the trends in the graphs improved when the lights and the Ondol control were altered. One set of notes indicated that the heating set point was 24C and another note indicated 22.5C. The measurements indicated the latter temperature and the fit improved when this change was made.

One set of changes related to climate uncertainty. The initial assessments used standard EPW climate data for Suwoon. Samsung wanted to find out if Korean MET office data or on-site weather data would be better sources. Data for Suwon were acquired, including data for the period of the experiments. Use of MET office data was seen to improve the fit between measurements and predictions. There were, however, differences in anbient temperatures and solar radiation for a number of hours where predictions diverged. Merging on-site data with the MET office data resulted in a slightly better fit. This last step might be considered to be at the point of dimensioning returns.

The next phase looked at the fit between observations and predictions in order to better understand the uncertainties in the model and the experiment. For example, the predicted floor temperature rise during and after the door open experiment was lower than observations but was generally correct prior to the experiment. Underestimating the heating density of the Ondol is consistent with such observations and a revised model showed a better fit.

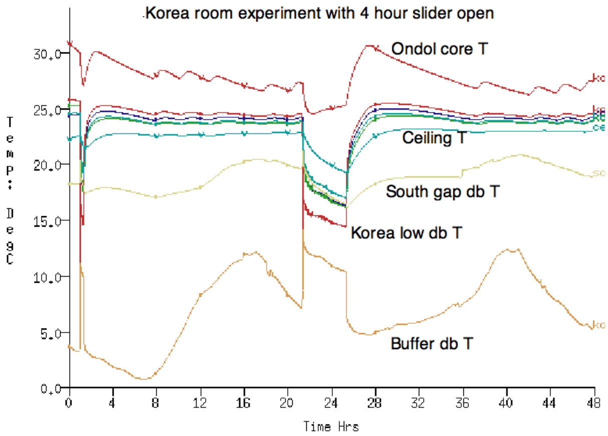

Figure 12 Typical graph from slider experiment

Infiltration was a substantial uncertainty identified in the blower door tests and in physical inspections. It is the elephant in the room that the simulation community is reluctant to talk aobut. Past efforts such as the Alberta Infiltraiton Method (Walker 1998) hint at the problem. In buildings with low fabric losses, infiltration uncertainty emerges as something that must be addressed.

During the heat-off experiment a change from crack flow component to a small orifice in the buffer space facade resulted in a much better fit. This magnitude of change was consistent with switching from dynamically assessed infiltration to scheduled air infiltration. Coincidence is not necessarily indicative of cause. What can be stated is that buildings which are designed for extreme performance are sensitive to small changes in infiltration and the selection of flow components is an important step in the design of models.

IMPLICATIONS ON MEDIUM TERM PREDICTIONS

The methodologies we use in model design and evolution has a broader implication for practitioners in terms of their impact on medium and long term predictions of performance. To clarify this the initial experiment-focused models were adapted for annual assessments and the differences noted.

Comparing the middle resolution models with the low resolution base case model yielded a one degree difference in the maximum and minim room air temperatures and resultant temperatures of the year. There was almost no different in heating kWhs or hours of demand. Simplifying the geometry resulted in an increase in cooling and cooling hours. Taking into account the experiment assessments brought the hours of heating demand into closer alignment.

Comparing the middle resolution model with the low resolution model with pure-convective heating results in closer control of temperatures and a quicker response than would be observed in an Ondol. Heating kWhrs is slightly less but the number of hours is much higher and the capacity needed for the pure-convective heating is 25% of the actual Ondol capacity. Thus a convective representation does not capture the capacity requirements of an Ondol or its response characteristics but does approximate long term demands.

Comparing the middle resolution model with the low resolution model with scheduled infiltration there was a two degree difference in maximum and minimum room air temperatures. The Ondol was seen to work harder. Heating kWhrs are substantially increased as are the number of hours of demand. Heating capacity has reduced because the dynamic assessment results in brief extremes that are not found in the static approach.

Comparing the middle resolution model with the low resolution model with an abstract roof results in small changes in peak temperatures reduced heating and increased cooling. The abstract representation lacks the large area of heat transfer at the roof and the thermophysical clutter in the ceiling void. It might be possible to adjust the outside heat transfer coefficient to compensate for this but there is no consensus on how to approach this. Other portions of the building differ between the ceiling form and the outer facade shape and thus this form of abstraction could have a noticeable impact on predictions.

Comparing the middle resolution model with a variant with addition leakage paths indicates the largest difference in long term performance. The buffer space maximum temperature is reduced by one degree and the minimum by six degrees. Heating kWhrs are substantially increased as are the number of hours of demand while cooling is reduced.

In comparison with the middle resolution base case the high resolution model sub-divides the Korea room into horizontal slices and also represents the spaces between the sliding paper doors and the buffer space sliding doors. There are more information points so it is possible to see an increased temperature adjacent to the Ondol as well as adjacent to the ceiling. The predictions for the temperatures in the single Korea room and the center slice of the higher resolution model are essentially the same. Thus an increase in resolution still provides the same essential information on the primary temperature in the Korea room.

The higher resolution model predicts lower heating demands over time and slightly fewer hours. This might be related to the increased thermal resistance between the Korea room and the buffer space due to the explicit paper slider representations

Comparing the high resolution model with a variant with additional leakage paths shows slightly greater temperature differences than the middle resolution model with and without additional leakage paths. The explicit gap zones provide additional buffering of the Korea room so the heating penalty is less than in the middle resolution model. In general the differences attributable to infiltration are greater than the differences attributable to geometric resolution.

CONCLUSIONS

The authors found that the observations during routine testing lead to insights which result in better fit physical and virtual experiments. Ad-hoc tests in existing buildings contribute to confidence in assessments as well as providing a focus for simulation staff to increase their skills.

The following findings may find application within the simulation community and in design teams. First, extending routine pressure testing and IR surveys to provide early indicators of building performance lead to better models as well as more focused follow-up experiments. Second, air and surface temperatures distributed within a room have been seen to act as proxies for air movement sensors for the intra-zone air flow test.

High resolution details needed to provide additional data points for experiments have minor impacts on longer term predictions. It proved difficult to represent the explicit gap zones in two states (door & screen closed and door & screen open) in the flow network. Altered geometric states of connecting zones is also a challenge to fully represent radiation exchange and solar penetration. For example, the optical properties of paper screens and the exterior wooden blinds were roughly approximated.

Substantial differences between the inner form and the facade can lead to over predict heating and underpredict cooling. Substitution of convective heating for Ondol heating implies loss of information on characteristic patterns of demand and comfort but only have a limited impact on annual kWhrs.

Infiltration proved to be the most difficult issue for measurements and changes in assumptions had the greatest impact on overall performance. Buildings designed for extreme performance are sensitive to small changes in infiltration and the selection of flow components is important.

More guidance is needed on how construction documents and site observations can be converted into flow networks. What would have helped would be a form of in-situ testing of facade elements for leakage characteristics with a higher resolution than the blower door test.

Extensive checklists on site are needed to ensure that models reflect the actual state of the building at different points during experiments. Model checking benefits from a close scan of performance data – for example, differences in cooling between the medium and high resolution models were eventually traced to slightly different setpoints.

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